UDC 621.376.56

BBC

1969 THE QUEEN'S AWARD TO INDUSTRY

RESEARCH DEPARTMENT

REPORT

Hybrid-pulse coding:
experimental equipment for tests with video signals

No. 1969/46

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

HYBRID-PULSE CODING: EXPERIMENTAL EQUIPMENT FOR TESTS WITH VIDEO SIGNALS

Research Department Report No. **1969/46**
UDC 621.376.56

It uses SI units in accordance with B.S. document PD 5686.

Work covered by this report was undertaken by the BBC Research Department for the BBC and the ITA

P.C.J. Hill, Ph.D., B.Sc., D.I.C., C.Eng., M.I.E.E.
R.J. Packer

D. Maurice
Head of Research Department

(EL-32)

Research Department Report No. **1969/46**

HYBRID-PULSE CODING: EXPERIMENTAL EQUIPMENT FOR TESTS WITH VIDEO SIGNALS

(EL-32)

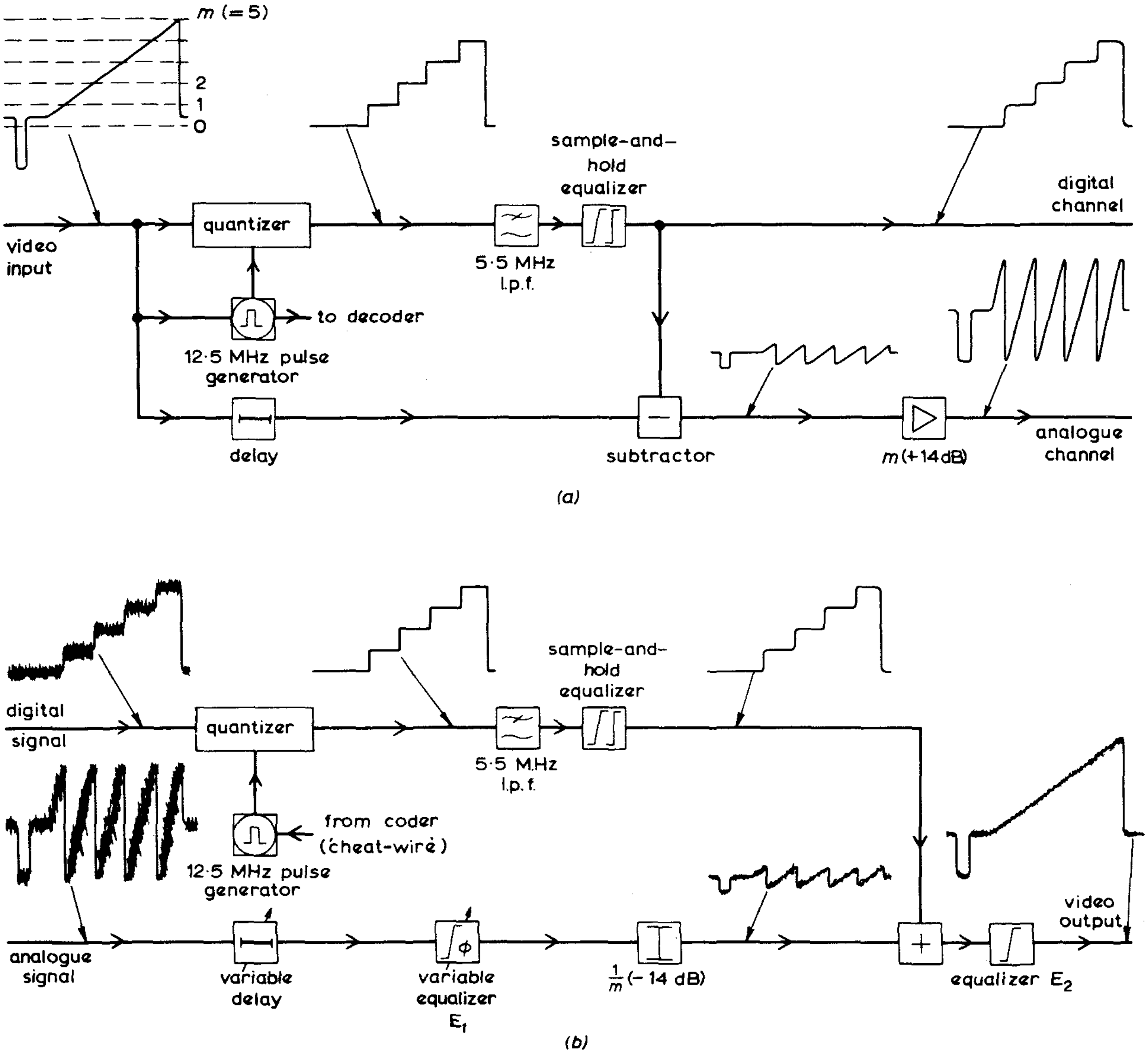


Fig. 1 - Simplified block diagram of twin-pulse h.p.c.m. system

(*a*) Hybrid coder (*b*) Hybrid decoder

November 1969

Research Department Report No. **1969/46**
UDC 621.376.56

HYBRID-PULSE CODING: EXPERIMENTAL EQUIPMENT FOR TESTS WITH VIDEO SIGNALS

SUMMARY

Hybrid-pulse coding (h.p.c.m.) is a method of coding a baseband signal into a moderately wideband channel in order to improve the noise performance of signal-processing and transmission systems. Previous Research Department Reports (Nos. 1969/40 and 1969/45) describe the principles of this coding system in some detail and also give the results obtained with experimental h.p.c.m. equipment for coding 625-line video signals.

The main instrumental problems which arise in such a system result from the process of splitting the original signal into separate multilevel digital and continuously variable analogue additive signal components. These two components undergo radically different processing but must remain complementary to one another so that the original signal can be accurately reconstructed by simple addition at the output of the receiving terminal.

The present report outlines the development of the experimental video equipment and highlights those features, peculiar to h.p.c.m. at video frequencies, which require special attention.

1. INTRODUCTION

Hybrid-pulse code modulation is a variant of multilevel p.c.m. which can improve the noise performance of channels used for signal processing and transmission in those cases where the signal bandwidth can be expanded by a factor of only two or three times. Previous Research Department Reports (Nos. 1969/40 and 1969/45)[1,2] have made a detailed assessment of this coding system and also described the results obtained using experimental vision equipment for hybrid-pulse coding 625-line PAL colour signals. The purpose of the present report is to describe the development of the experimental equipment used in this feasibility study and, in particular, to examine the instrumental problems peculiar to hybrid-pulse coding.

The main instrumental problems which arise in h.p.c.m. systems result from the fact that the original signal is split into a multilevel digital component and a continuously variable analogue component. Subsequent signal processing in the transmission channel and in the hybrid decoder must preserve the complementary nature of these two components so that the original signal waveform can be accurately reconstructed at the receiving terminal by simple addition after regeneration of the digital component. Digital regeneration is performed in a quantizer which incorporates sampling processes and it is therefore essential to synchronize this operation with that of the quantizer in the hybrid coder at the sending terminal; in addition to this, the relative phase of the analogue and digital components must be accurately maintained.

The experimental equipment consisted of a sending terminal for hybrid-coding 625-line PAL composite colour signals into two separate 5·5 MHz analogue and digital channels, together with a receiving terminal for regenerating the digital component and reconstructing the original 5·5 MHz vision signal; the digital component was quantized into 5 levels. A third channel served as a 'cheat-wire' providing synchronization for the hybrid-decoding operation. Designing equipment of this kind for colour signals involves no further instrumental complexity than for monochrome signals but the requirements of colour in terms of waveform reconstruction accuracy are much more severe; this is because when colour is present, the signal waveform can excurse through many digital levels at high (i.e. subcarrier) frequency.

The essential scheme of the h.p.c.m. equipment is shown in the block diagram of Fig. 1. In the hybrid coder, Fig. 1(*a*), the multilevel digital signal at the output of the quantizer is applied to a video low-pass filter. The analogue signal is proportional to the instantaneous difference between the input video signal and the filtered digital signal. Its peak amplitude is $1/m$ of the available modulation depth in the digital channel where m is the number of quantizing levels;* the analogue signal is therefore amplified by the factor m prior to being transmitted.

In Fig. 1(*b*), the components of the hybrid decoder required to regenerate multilevel signals from the received channel signal are identical to those in the coder. Here, the analogue signal is attenuated by the factor m and then added to the regenerated multilevel signal, which has been restricted to video frequencies by a low-pass filter, thus reconstructing the original input signal. Fig. 1 shows the input picture signal as a sawtooth, and also gives the corresponding waveforms at other points in the circuit to illustrate the processing operations involved in h.p.c.m.; channel

* the quantizing levels are numbered 0, 1, 2, ..., m.

noise and its subsequent modification during processing are represented by irregular additions to the idealized waveforms.

In the following discussion, special emphasis is given to those features in the design of video h.p.c.m. equipment which are important for ensuring good accuracy in the picture reconstruction process.

2. EXPERIMENTAL EQUIPMENT FOR FEASIBILITY STUDY

2.1. General

In the experimental equipment (Fig. 1), up to ten levels of quantizing were originally provided but only five levels were finally used for the experimental work as this number (i.e. $m = 5$) was later shown[1] to offer the largest signal-to-noise improvement ($\simeq$ 14 dB) consistent with an acceptable digital error rate (one per frame); this result can be achieved with a channel signal-to-noise ratio of 34 dB (peak video-to-unweighted r.m.s. noise).

In the coding process (Fig. 1(*a*)), the sawtooth input is quantized into five levels; black level is situated half way between levels '0' and '1' of the threshold detectors in the quantizer and peak white extends to level '5'. This arrangement of levels has the advantage of symmetrically quantizing the colour-burst signal (Reference 2, Fig. 7); it also further improves the signal-to-noise advantage by not transmitting the full amplitude of the synchronizing pulses, which can be regenerated at the receiving terminal. The multilevel signal is restricted to video baseband frequencies through the 5·5 MHz low-pass filter and equalizer. The difference signal from the subtractor is similarly band-restricted and is amplified by 14 dB (i.e. $20 \log_{10} 5$) for transmission in the analogue channel to the decoder.

At the decoder, the multilevel digital signal is re-quantized in order to remove noise from the digital channel. The original sawtooth waveform is reconstructed by combining the 5·5 MHz filtered multilevel signal with the analogue signal which is attenuated by 14 dB; noise in the analogue channel is thus reduced by the same figure. It is important that these waveforms are made complementary to one another in respect of both amplitude variation and time-displacement in order to avoid errors in waveform reconstruction. Delay networks are introduced in both coder and decoder to compensate for the propagation time in the quantizers and filters; each filter is followed by a sample-and-hold equalizer. The decoder incorporates amplitude and phase equalizers in the analogue channel (Fig. 1(*b*)) in order to reduce residual waveform errors.

2.2. Special Requirements

It will be observed that the basic processing operations involved in h.p.c.m. are common to the sending and receiving equipment. The nature of the system requires certain essential similarities between the coder and decoder units in order to reconstruct video signals of sufficient accuracy for acceptable 625-line colour pictures. The required instrumental similarities between the coder and decoder become very stringent with an h.p.c.m. system working in the minimum bandwidth of 11 MHz, i.e. 5·5 MHz per channel.

In order to achieve the full noise improvement from an h.p.c.m. system of minimum bandwidth it is essential to employ time-sampling in the quantizers.[2] This artifice is also convenient for instrumental reasons; the output sample-and-hold units reduce digital errors due to transient currents in the summing switches.[3] At the hybrid decoder, the digital waveform from the output sample-and-hold must be as similar as possible to the corresponding output at the coder in order to avoid errors in waveform reconstruction;

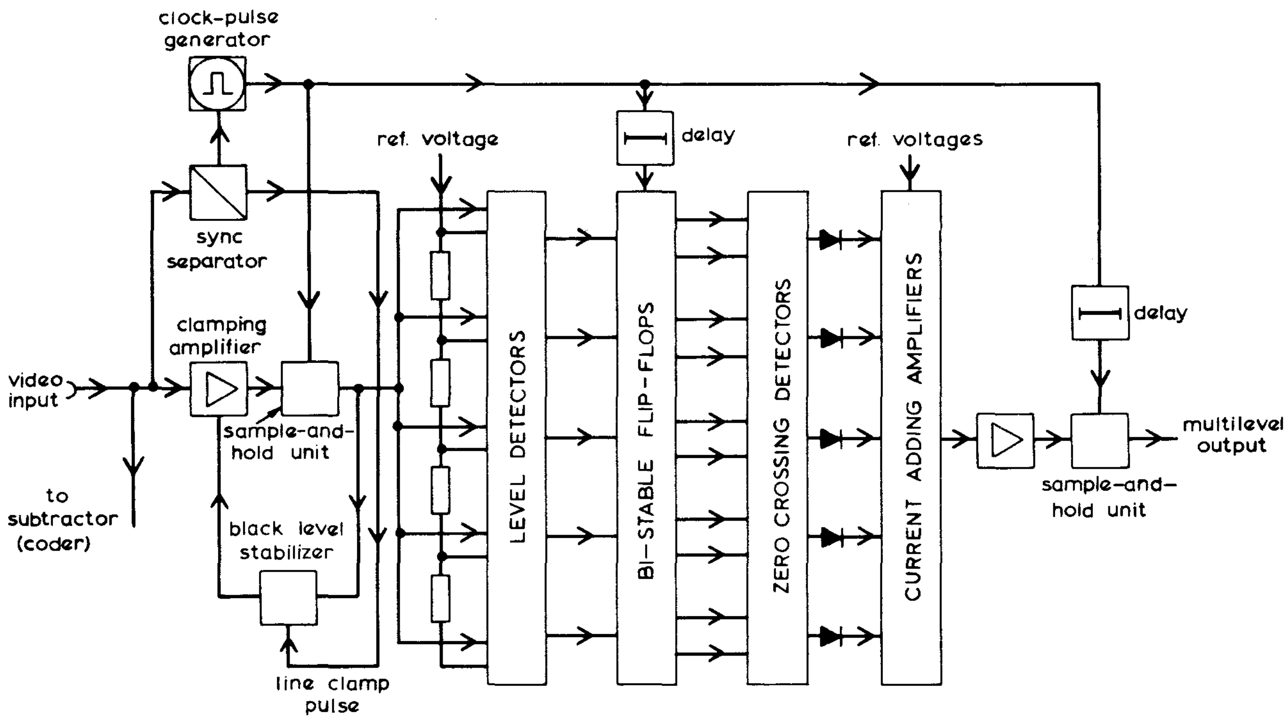


Fig. 2 - Schematic arrangement of sampling quantizer

apart from circuit considerations, this demands accurate clock synchronization. Although initial experiments showed the possibility of synchronizing the hybrid coder and decoder by regenerating clock pulses from either the digital or the analogue representations of the colour-burst signal, a cheat-wire was employed for the experimental tests to provide an independent synchronizing signal. The clock pulses to the decoder were delayed by a time interval equal to the propagation time in the coder; a small variable delay was also provided for adjustment purposes.

The filtered multilevel components are required to be exactly sinx/x in form in order that the noise advantage is not reduced by interpulse crosstalk and it is therefore necessary to generate the fastest possible pulse edges at level transitions in the quantizer outputs; as stated previously, for accurate waveform reconstruction, these pulse shapes must be identical in both coder and decoder. Good matching is also required between the low-pass filter characteristics and also between the sample-and-hold equalizers which compensate for high-frequency losses incurred through the waveform holding operation. The analogue signal at the decoder is not subject to regeneration and has only to be correctly delayed and equalized for frequency-dependent errors before being summed to the multilevel signal.

2.3. Special Features

2.3.1. Quantizers

The essential components of the quantizers are shown in Fig. 2; the detailed design* is outside the scope of this report. Each sample-and-hold unit incorporates a diode-bridge circuit (a similar but more advanced arrangement is described in Reference 4); the input sample-and-hold unit operates in conjunction with a black-level stabilizing circuit.[5] The sampled-and-held signal is applied simultaneously to the inputs of five integrated-circuit (i.c.) level-detectors (type μA710). Reference voltages for the level-detectors are supplied by a ladder network fed from a constant-voltage source; the voltage steps are made accurate to 0·2%. Individual detectors provide outputs during the period over which the input level exceeds their respective reference voltages. The effect of indecision in level-detection, which can occur during hold periods when the input signal is close to the reference level, is avoided by converting the output transitions into pulses of full clock-period duration, using bi-stable integrated circuits (type MC1016P); these circuits are re-set at the end of successive clock periods. The accuracy of the multilevel components is further improved by slicing at the zero-crossings in the bi-stable outputs with level-detectors (type μA710); the outputs of the zero-crossing detectors operate current-adding switches to provide the complete multilevel digital signal. A second sample-and-hold operation on the multilevel signal removes the effects of switching transients which appear in the output of the current-adding amplifiers.

* due to J.P. Chambers.

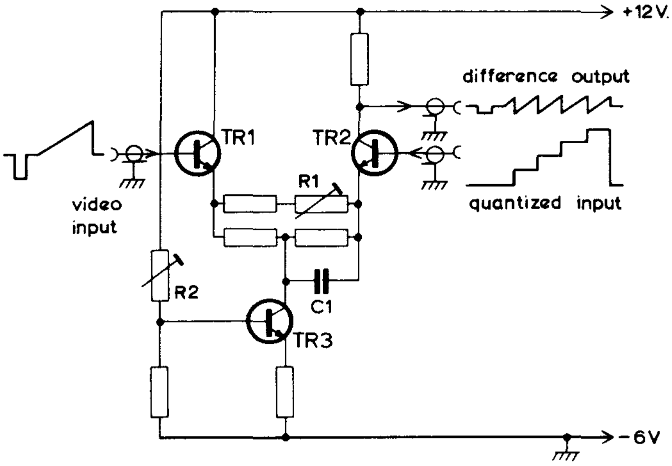


Fig. 3 - Simplified circuit of the subtractor unit

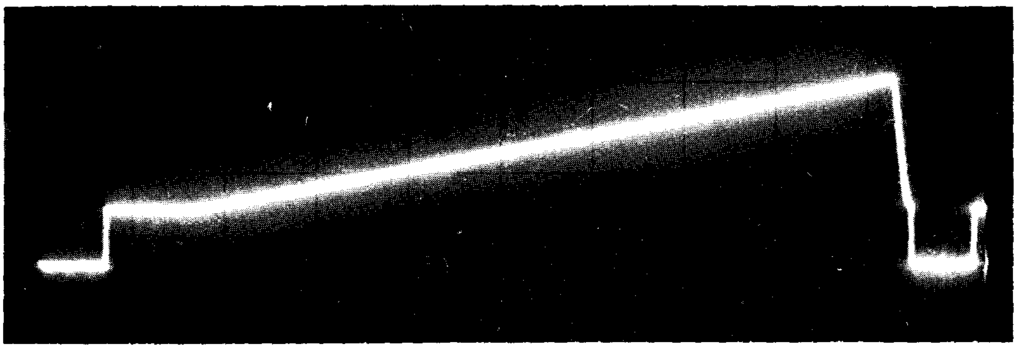
2.3.2. Subtractor

The subtractor circuit (Fig. 1(*a*)) is shown in simplified form in Fig. 3. Identical signals present at the base and emitter of transistor TR2 would have opposing effects on the collector current but a difference signal is generated at the collector of TR2 when independent base and emitter signals are present. Transistor TR3 is a high impedance element which improves the accuracy of the subtractor and, together with transistor TR1, adequately isolates the two independent inputs. The gain in the collector circuit of TR2, which was made adjustable (R_1) over a small range, partially restores the amplitude of the difference signal to a value suitable for final amplification. Linearity of the output difference signal can be achieved by adjusting resistor R_2.

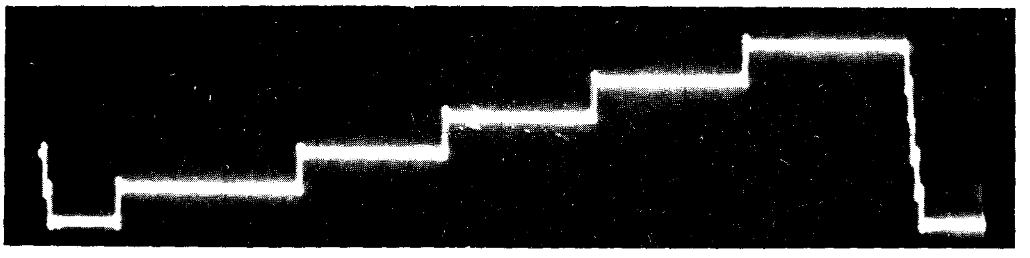
It will be observed that for signals entering the emitter of transistor TR2, operation is in the common-base mode whereas for signals present at the base, a common-emitter mode applies. The gain-bandwidth product of the transistor is lower in the common-emitter mode so that the two components in the difference signal will be subject to different gain-frequency characteristics. However, the f_T for the transistor employed was in the region of 350 MHz and the difference between the frequency characteristics in the two modes was not large; residual errors due to this and other causes were eliminated by equalization with capacitor C_1.

2.3.3. Filters and Equalizers

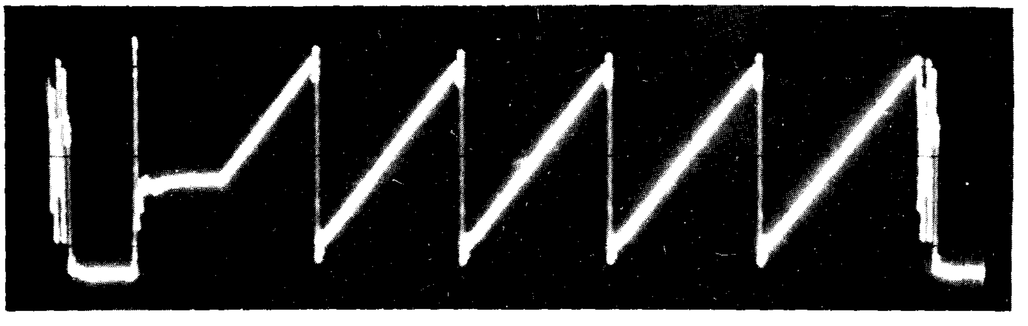
The equipment employs three-section 5·5 MHz channel filters of antimetric[6] design; each filter is followed by a four-section all-pass group-delay corrector. The maximum cut-off rate of this combination was approximately 50 dB per octave, and the minimum stop-band attenuation, 30 dB; this led to a sampling frequency of around 12·5 MHz. Equalization of the sampled-and-held multilevel waveforms, amounting to 4 dB at half-sampling frequency, was carried out with conventionally designed 'twin-T' constant impedance networks. Individual adjustment was made to the filter-equalizer combination in the coder and



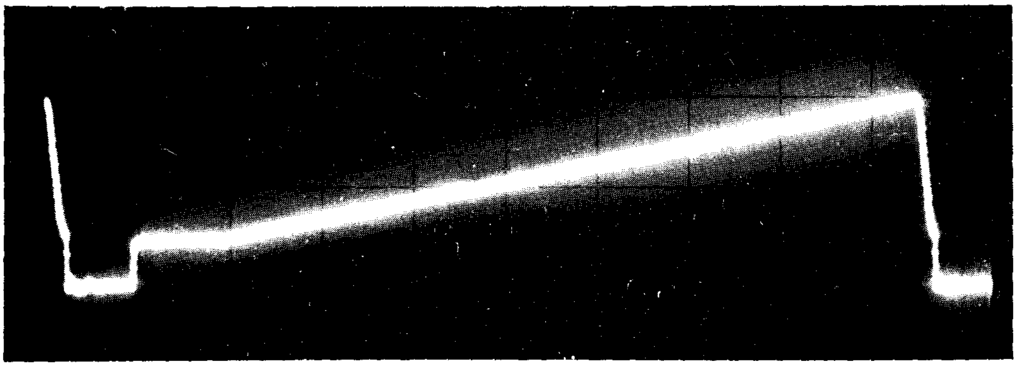
(*a*) Input signal, coder



(*b*) Digital component



(*c*) Analogue component



(*d*) Reconstructed output signal, decoder

Fig. 4 - Reconstruction of a linear sawtooth waveform

decoder to ensure identical frequency response characteristics. Final adjustment was performed by simultaneously displaying the impulse responses of the two combinations in order to obtain equally spaced zero-crossings in both output waveforms.

2.3.4. Delay Units

The design of the main delay networks in the hybrid coder and decoder followed well-known principles. The delay units for the analogue channels were lumped-circuit lines providing about 750 ns delay from coupled sections (with negative mutual inductance between coils) with individual delays of 16 $^{2}/_{3}$ ns; fine delay adjustment was obtained by tapping into printed copper strip delay lines* having ¾ ns delay between taps. Clock pulse delay over both sampling quantizers was obtained from fixed lengths of co-axial cable, whereas the main clock-pulse feed to the hybrid decoder was fed via an adjustable printed circuit delay line of the type described above.

2.3.5. Summing Amplifier and Equalizers – Decoder

A passive network was employed to sum the analogue and regenerated multilevel components in the decoder. Frequency-dependent errors can exist in either of these component signals and their effect on the output signal was most easily observed and measured by reconstructing multiburst and pulse-and-bar test signals. Instrumental errors in the digital signal arose from dissimilarities between the filtered sampled-and-held outputs of the coder and decoder whereas those in the analogue signal were due primarily to transmission-frequency distortion introduced by the delay networks; in practice, the channel link used will introduce further errors which may affect both signal components.

In principle, the frequency-dependent errors in each channel can be equalized individually prior to summation of the two components. However, in order to obviate the difficulty of separate and interdependent adjustments to each signal component, equalization was performed in two stages. Referring to Fig. 1(*b*), a variable equalizer E_1 was placed in the analogue channel and adjusted so that on summation this signal became complementary to the unequalized digital component at level transitions. A second equalizer E_2 placed after component summation corrected the overall frequency response of the reconstructed signal. Experiment showed that a conventional double time-constant phase equalizer would suffice for E_1 and a simple amplitude equalizer for E_2; no further phase correction was required.

3. PERFORMANCE OF THE EQUIPMENT

Analogue and digital measurements were made in order to determine the objective performance of the main units in the h.p.c.m. equipment.

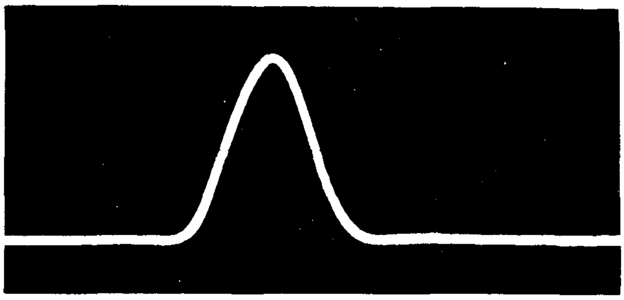
The performance of the hybrid coder depends to a very large extent on the accuracy of the subtraction process for forming the analogue signal. This accuracy was tested by reconstructing a sawtooth waveform immediately after subtraction; the mean ratio of the peak-peak error occurring at level transitions to the peak video signal was about 0·5% (−46 dB), which was considered satisfactory.

The performance of the hybrid decoder on the other hand is dictated by both the accuracy of the digital regeneration process and also by the amplitude-and-phase frequency characteristics of the analogue channel. The digital accuracy is mostly determined by the degree of similarity of the output stages of the quantizer to those in the hybrid coder; these stages include the final sample-and-hold circuit and equalizer together with the baseband low-pass filter. In addition, high-frequency signals with large amplitudes (saturated colours) demand particularly accurate sampling in the quantizer itself in order to avoid digital errors. The frequency characteristics of the active analogue circuits were satisfactory but those of the delay line sections alone corresponded to a k_{1T}-rating of about 1% and therefore required some equalization. The nature of equalization in the decoder (Section 2.3.5) was such that it was not necessary to equalize the delay line separately; phase equalization was performed prior to addition of the analogue and digital components and amplitude equalization after addition of the signal components (Fig. 1(*b*), E_1 and E_2 respectively). The phase equalization was adjusted in combination with line-delay variation to minimize waveform errors at level transitions. With careful adjustment, the ratio of the peak-peak error at level transitions to the peak video signal did not exceed 1% (−40 dB); this error was just perceptible with sawtooth and colour-bar signals. The amplitude equalization of the reconstructed signal ensured an adequate performance with the test pictures used.

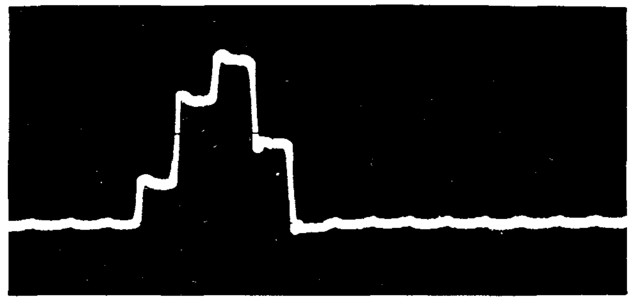
A pictorial record of the performance of the equipment is given by Figs. 4, 5 and 6. Stages in the reconstruction process of a linear sawtooth signal are shown in Fig. 4 as oscilloscope records; waveform (*a*) is the input signal. Intermediate waveforms (*b*) and (*c*) were in fact taken from the coder but the corresponding waveforms in the decoder differ insignificantly from those shown; the output sawtooth (*d*) exhibits waveform reconstruction errors which are just perceptible. Fast pulse inputs provide a more critical test of the instrumentation. Fig. 5 shows various stages in the reconstruction of a 5·5 MHz $\cos^2 x$ pulse ($2T$-test pulse); the output pulse (*e*) is a fairly accurate copy of the original $\cos^2 x$ waveform but there is some ripple following the main lobe. The mechanism of hybrid coding at level transitions is illustrated in Fig. 6 which shows time-expanded waveforms at the decoder corresponding to a sawtooth input signal; the latter half of each waveform has been time-expanded. The oscillatory nature of the complementary waveforms (Fig. 6(*b*)) is due to the 5·5 MHz low-pass filter and equalizer units.

The ultimate test of instrumental performance is the quality of the output pictures. Subjective tests[2] showed that the net impairment of h.p.c.m. colour pictures due to processing alone amounted to about ½ EBU grade. It is

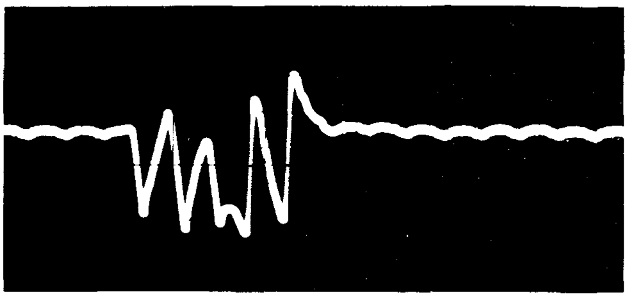
* experimental printed circuit delay lines supplied by M.E.L. (Mullard).



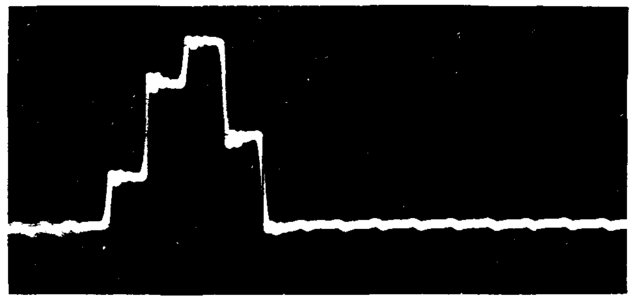
(*a*) Input pulse, coder



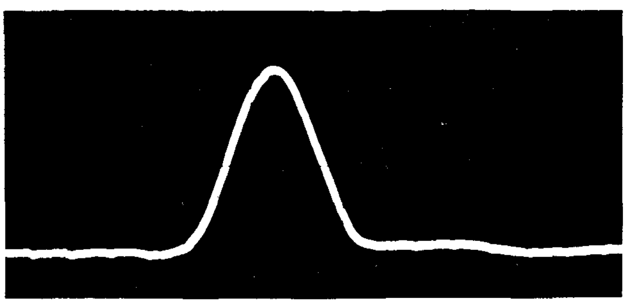
(*b*) Multilevel component, coder



(*c*) Analogue component, coder



(*d*) Regenerated multilevel component, decoder



(*e*) Reconstructed output pulse, decoder

Fig. 5 - Reconstruction of a $\cos^2 x$ *2T-pulse*

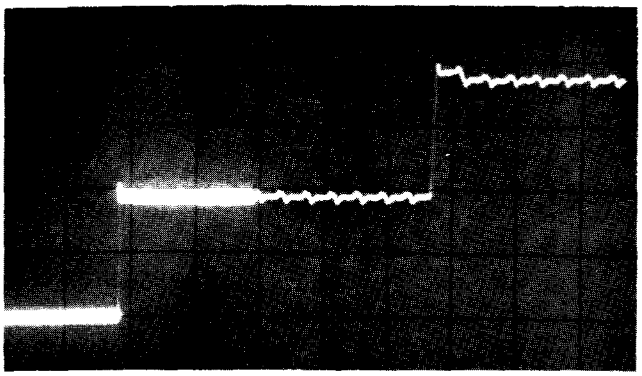
estimated that the waveform reconstruction errors in the hybrid decoder would have to be reduced by about 6 dB in order to render them imperceptible.

Initial experiments with the equipment also demonstrated that it would have been possible, at the expense of some further instrumentation to synchronize the clock signal in the hybrid decoder either to the analogue or to the digital component of the colour subcarrier burst, using the third harmonic ($\simeq$ 13·3 MHz) for clock regeneration.

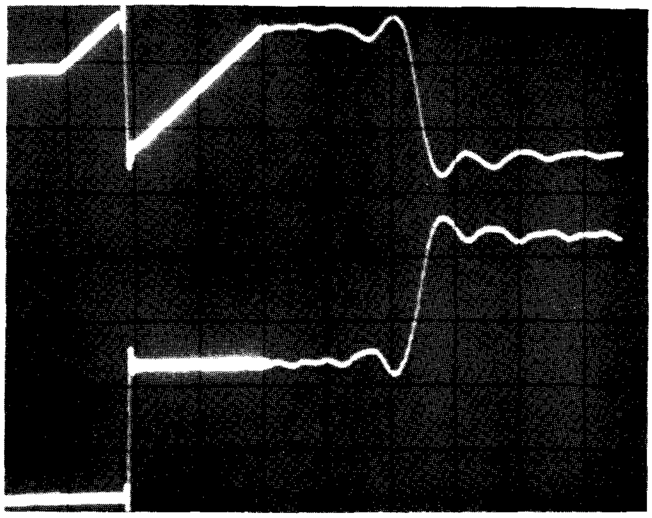
5. CONCLUSIONS

The performance of the experimental equipment described here was adequate for the practical feasibility study of hybrid-pulse coding 625-line PAL colour signals and the investigation into the noise performance of the system, described in the earlier report. There were some instrumental limitations, however, which slightly degraded the quality of h.p.c.m. colour pictures. This impairment, which resulted from residual waveform errors at level transitions in the picture reconstruction process, amounted to about ½ EBU grade. It is thought that by further instrumental development the net picture impairment could be made negligible.

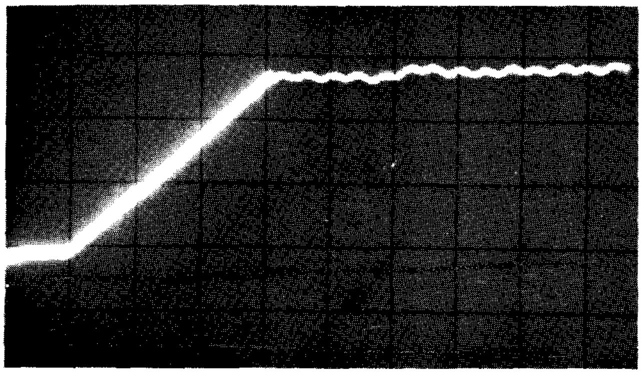
The instrumentation of the digital channel in the h.p.c.m. equipment, employed modern integrated circuits of both linear and digital type, and the techniques evolved are equally applicable to other forms of digital television which employ multilevel coding.



(*a*) Regenerated multilevel signal



(*b*) 5·5 MHz analogue and digital components



(*c*) Reconstructed waveform

Fig. 6 - Performance of h.p.c.m. equipment at level transitions: expanded decoder waveforms

6. REFERENCES

1. Hybrid-pulse coding — theoretical assessment of system. BBC Research Department Report No. 1969/40, (EL-30).

2. Hybrid-pulse coding — experimental assessment of system as applied to video signals. BBC Research Department Report No. 1969/45, (EL-31).

3. KOVANIC, E.F. 1963. A high-accuracy 9-bit digital-to-analogue converter operating at 12 Mc. *IEEE Trans. Comms and Electronics*, 1964, 71, pp. 185 – 191.

4. GRAY, J.R. *and* KITSOPOULOS, S.C. 1963. A precision sample and hold unit with sub-nanosecond switching. *IEEE Trans. Circuit Theory*, 1964, **CT-11**, 3, pp. 389 – 396.

5. Experimental equipment for converting television signals into digital signals and vice versa. BBC Research Department Report No. EL-14, Serial No. 1968/6.

6. SKWIRZYNSKI, J.K. 1965. Design theory and data for electrical filters. London, *Van Nostrand*, 1965, pp. 68 – 70.

SMW

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey